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Improving hydrodynamic efficiency of composite marine propellers in off-design conditions using shape memory alloy composite actuators

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ABSTRACT

The bend-twist coupling of fibre-reinforced composite laminates has been studied extensively to introduce self-adjustment in pitch angle of marine propellers for improving the hydrodynamic efficiency in off-design conditions. A recent study has shown that for full-scale propellers designed against material failure, the twist generated in the deformed blade due to this effect is not sufficient to cause any noticeable change in the hydrodynamic efficiency. In this paper, we study the use of shape memory alloy (SMA) for inducing variable twist in composite propellers for achieving the same. Prestrained SMA fibres are embedded in the composite in the martensite phase. When SMA fibres are heated upto the austenite phase, a large recovery stress is developed due to the shape memory effect. This stress is used to create twist in the propeller blade through appropriate positioning of the SMA actuators. A full-scale propeller of 4.2 m diameter, made of graphite epoxy with Nitinol fibres as SMA, is considered. The study establishes for the first time that using SMA composite actuator elements, it is possible to generate sufficient twist that can cause the desired improvement in the hydrodynamic performance of full-scale marine propellers at off-design conditions over a wide range of advance ratio.

1. Introduction

Marine propellers, operating at different advance ratios, cannot maintain its peak efficiency throughout the entire operational regime. This is due to the fact that the angle of attack of the incidental flow changes with advance ratio and only at one angle of attack, the efficiency becomes maximum. A propeller is normally designed to operate at a particular advance ratio, where it exhibits nearly maximum of hydrodynamic efficiency. However, many propellers need to operate at off-design conditions also (e.g., tugs and trawlers or a high speed attacking frigate). If the pitch of propeller blade remains fixed, in such operating conditions, the suboptimal angle of attack gives lesser hydrodynamic efficiency. There has been an enormous interest among researchers and engineers for enhancing the hydrodynamic efficiency of marine propellers required to run often in off-design conditions, since it can lead to significant reduction in the operating cost due to fuel saving. In a controllable pitch propeller, the pitch can be manually adjusted to adapt to different operating conditions (Das et al., 2012). However, the additional mechanical arrangements required to make these adjustments demand a larger diameter of the hub, which may constrict the space for the propeller blade.

Metallic propellers do not undergo any significant twisting deformation under hydrodynamic loading so as to alter its effective pitch depending on the operating condition (Das et al., 2013). With the introduction of laminated fibre reinforced composite materials, the material anisotropy can be used to generate twist in the propeller blade from its bending under the action of hydrodynamic loading. This twist alters the effective pitch of the revolving propeller, which may be harnessed to improve the hydrodynamic performance at off-design conditions. The study on the behaviour of composite propellers to exploit the advantages of its flexibility and tailorability can be traced to Lin (1991) who presented a numerical simulation of composite marine propellers using the vortex-lattice method (VLM) for computing the flow and its associated hydrodynamic pressure, and the finite element method (FEM) for the stress analysis, without considering the fluid-structure coupling effect. More recently, Young (2008) used a panel based boundary element method (BEM) for flow analysis instead of the VLM, and the FEM for the structural analysis considering the geometric nonlinearity due to large displacements of the flexible composite blades. The coupling effect between the deformation and the fluid pressure distribution was considered by updating the blade geometry after the structural analysis and performing the deformation and flow

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analyses iteratively. Motley et al. (2009) showed through a numerical study that in off-design conditions, composite propellers exhibit higher efficiency than their metallic counterparts owing to the twist caused by the bend-twist coupling effect. Liu and Young (2009) optimized the performance enhancement of self-twisting composite marine propellers by maximising the ratio of change in twist of tip to change in hydrodynamic loading. Mulcahy et al. (2010) demonstrated that the flexible composite marine propellers can be hydroelastically tailored to yield improved hydrodynamic efficiency over a range of operating conditions. A number of studies have focussed on the optimization of the laminate layup of composite marine propellers to maximize the bend-twist coupling (Lee and Lin, 2004; Herath and Prusty, 2012; Herath et al., 2013, 2015) and to reduce the vibratory hub loads (He et al., 2012). All the aforementioned studies on the use of bending-twist coupling of composite marine propellers for improving their hydrodynamic performance have, however, been made on model propellers of small size ($\sim$0.3–0.6-m diameter). The extrapolation laws for hydrodynamics and structural deformation being different, these results cannot be readily correlated with the prototype propellers which are of much larger size ($>$ 4 m diameter).

A full-scale composite propeller of 4.4 m diameter was studied by Blasques et al. (2010) using the coupled BEM-FEM for analysis, who reported a reduction of the combined fuel consumption of 1.25% and zero reduction for the maximum speed condition for the composite propeller compared to its metallic counterpart. Motley and Young (2011) presented a probabilistic performance-based design method for flexible marine propellers, wherein a full scale composite propeller of 5.18 m diameter was designed, but no improvement in the hydrodynamic efficiency was observed. These studies, however, had not considered the viscous flow, which can have significant influence on the hydrodynamic loading and consequently the deformation behaviour. The authors (Das and Kapuria, 2016) have recently presented a comprehensive study on the use of bending-twist coupling of composite laminates in improving the hydrodynamic efficiency of full scale composite propellers at off-design conditions, considering viscous flow and accounting for the material failure check. The study revealed that the twist generated in the full scale propeller is inadequate to create any noticeable change in its hydrodynamic efficiency, for the commonly used composite materials within the limits of material failure. However, when material failure was ignored, it was possible to achieve significant (5.2%) improvement in the hydrodynamic efficiency in off-design conditions. It was suggested that the development of new composite materials with higher strength or use of smart materials to generate the requisite twist can be the possible options for harnessing the potential of flexible composite propellers in improving hydrodynamic performance.

Among various smart materials, shape memory alloys (SMAs) seem to be very effective for structural shape control due to the large strain ($\sim$6–8%) they can produce with the change in temperature (Duerig et al., 1990). SMAs are materials that have the ability to memorize its shape at one temperature (low), undergo large quasi-plastic deformation (extension, bending or twisting) at this temperature and then recover its original shape at a different temperature (high) through phase transformation. This phenomenon is called the shape memory effect (SME). When an SMA wire, prestrained (or plastically deformed) in the room temperature phase (martensite phase), is constrained mechanically or elastically (by embedding in a composite matrix), upon heating up to the high temperature phase (austenite phase), due to the SME and the constraint against strain recovery, a large tensile recovery force develops. This force can be used to achieve adaptive control of stiffness and shape of structures.

A comprehensive review of the research, applications and opportunities for SMAs has been recently presented by Jaronie et al. (2014). There are three distinct configurations of using SMA wires to control the structural response: (i) connecting externally to the host structure (Baz et al., 1990; Roglin and Hanagud, 1996), (ii) embedding in composite structures, and (iii) inserting in composite structures through sleeves (Ro and Baz, 1995). The concept of embedding SMA wires in a composite laminate to create what is known as the shape memory alloy hybrid composite (SMAHC) was introduced by Rogers and Robertshaw (1988). Subsequently, the SMAHC has been studied for active control of vibration (Rogers et al., 1991; Turner et al., 1994), post-buckling (Lee and Lee, 2000; Roh et al., 2004; Asadi et al., 2016; Kamarian and Shakeri, 2017) and flutter (Samadpour et al., 2016). Due to low frequency actuation ability, however, SMAs are better suited for shape control applications. Chandra (2001) successfully induced bending and twisting in a composite beam for helicopter blade control using SMA elements. The shape control of SMAHC beams, plates and shells has been studied by Daghia et al. (2008), Cho and Rhee (2012) and Bodaghi et al. (2014). Bil et al. (2013) have studied the morphing control of small and medium-sized unmanned air vehicle wings using the SMA actuators for maximising endurance for a given fuel load. Park et al. (2011) have presented the design and performance analysis of a variable-twist tiltrotor blade (also known as proprotor) using the SMAHC for achieving improved aerodynamic performance in both helicopter mode and airplane mode conditions. No prior work could, however, be found on the use of SMA actuators for twist control of marine propellers.

In this work, we study the use of SMAHC actuators for inducing variable twist in composite marine propeller blades for improved hydrodynamic efficiency in off-design conditions. A full-scale propeller of 4.2 m diameter is considered for the study, accounting for the viscous turbulent flow, geometric nonlinearity and the material failure check of the composite laminate. The fluid-structure interaction is implemented iteratively. The thermomechanical behaviour and the recovery stress of the SMA fibres are predicted using the Brinson model (Brinson and Lammering, 1993), and the effective material properties of the SMAHC are determined using the strength of materials approach. The optimal placement of the SMAHC actuators for maximum twist and twist control by change of temperature of SMA wires are studied.

2. Shape memory alloy modelling

In the absence of stress, an SMA material at high temperatures exists in the parent austenite phase (body-centered cubic crystal structure, state A) and upon decreasing the temperature, the crystal structure undergoes a self-accommodating crystal transformation into martensite (face-centered cubic structure, state B). The crystal structures are schematically shown in Fig. 1 (a). The transformation from austenite to unstressed martensite results into the formation of evenly distributed multiple martensitic variants and twins. All of these variants are crystallographically equivalent, differing only by habit plane indices, and each variant consists of two twin-related martensites. In this configuration, different variants have different orientations due to different indices. When a critical stress is applied (Fig. 1(a) and (b)) on this self-accommodating martensite, these twins undergo large reversible strains to transform into detwinned martensite (state C). Depending upon the alignment of the habit planes and the axis of the loading, all the variants align themselves in a single preferred direction. This single variant of martensite is thermodynamically stable at temperatures less than the austenite start temperature (A_s) and no reverse transformation to multiple variants takes place after unloading. Therefore when load is removed, only a small elastic strain is recovered, leaving the material with a large residual prestrain (state D). However, if the maximum strain in the martensite phase is below the second yield point, the entire prestrain can be recovered by heating the specimen above the austenite finish temperature (A_f) by which it transforms to original body-centered cubic austenite phase (state A) and thereby creating the shape memory. For Nitinol, upto 8% strain is fully recoverable. For Cu—Al—Ni and Cu—Zn—Al alloys, the maximum recoverable strain is of the order of 3–5%.

However, while raising the temperature above A_f, if the SMA with